Research on Both the Dynamic Characteristics of Superheavy Powerful Turning and Cutters' Life

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***Abstract*-Based on the cutting experiments of a hydrogenated cylindrical shell material 2.25Cr-1Mo-0.25V steel, this paper analyses the dynamic mechanical properties of extremely heavy-duty cutting, studies the influence of dynamic mechanical properties on cutting tool failure during extremely heavy-duty cutting, and builds a dynamic shear mechanical model for the cutting zone. The results of those experiments show that the flow stress of dynamic shear in the zone has a greater influence on the fatigue of the tool and the main damage form of the heavy-duty turning tool is shear fractures. After taking comprehensive theoretical analyses, it determines the critical condition of fracture failure for turning tools under extremely heavy-duty conditions.**

Keywords-Extremely Heavy-duty Cutting; Shear Flow Stress; Dynamic Cutting Force; Fatigue Rupture; Dynamic Strength

I. INTRODUCTION

In general, cutting process is divided into steady cutting and dynamic cutting: a cutting process without vibration is called steady cutting process; a cutting process with vibrations or impacts is called dynamic cutting process [1, 2]. Large rough cylindrical shell forgings (such as the cylindrical shell section) have many forging defects on the surface. In the process of cutting, cutting conditions, cutting cross-sections, working angles of tools, cutting tool-scrap-work-piece contact state and other states are changing all the time, so both cutting force and cutting temperature have dynamic characteristics, and these characteristics often result in premature failures of tools. The late 1950s, Kececioglu first studied the dynamic mechanical properties of metallic materials through the first deformation zone in metal cutting process and pointed out that the shear flow stress of steel increased with the increase of shear strain rate [3]. Stevenson and Oxley thought through the influence of strain, strain rate and temperature on the dynamic characteristics of cutting on the basis of the cutting models of parallel-changing shear zone [4], which laid a theoretical foundation for the research on the dynamic mechanical properties of cutting and tool failure. However, these researches are based on ordinary cutting and haven't involved the detailed study of extremely heavy-duty cutting yet. Therefore, the study on the dynamic mechanical properties of extremely heavy-duty cutting and the conditions of tool failure has positive significance to the accurate prediction of cutting process.

II. DYNAMIC MECHANICAL PROPERTIES OF EXTREMELY HEAVY-DUTY CUTTING

Rough machining of cylindrical shell section is a dynamic intermittent cutting process, whose cutting depth changes a lot (a_p =0~50mm). Because the cutting edge angle of heavy-duty turning tool is between 45° and 60°, cutting width a_w is significantly greater than cutting thickness a_c and cutting depth a_p. Therefore, the deformation degrees of all the sections of cutting edge are roughly the same. When the cutting speed exceeds the range of BUE cutting speed, the first deformation zone is in line with the parallelogram theory proposed by Oxley (as shown in Fig.1), and shear flow stress τ_{AB}, shear strain rate δ_{AB} and shear strain of γ_{AB} can be obtained after analysing Fig. 1 (as shown in Eq. 1):

$$\begin{cases} \tau_{AB} = \dfrac{F_H \sin\theta}{a_c a_w} = \dfrac{(F_z \cos\theta - F_x \sin\theta)\sin\theta}{a_c a_w} \\ \delta_{AB} = \dfrac{\upsilon_H}{H} = \dfrac{\upsilon \cos\zeta_o}{H\cos(\theta-\zeta_o)} \\ \gamma_{AB} = \dfrac{\cos\zeta_o}{2\sin\theta\cos(\theta-\zeta_o)} \end{cases} \tag{1}$$

Where, υ_H is the shear velocity of *AB* plane. *H* is the width of the parallel edge in the shear zone.

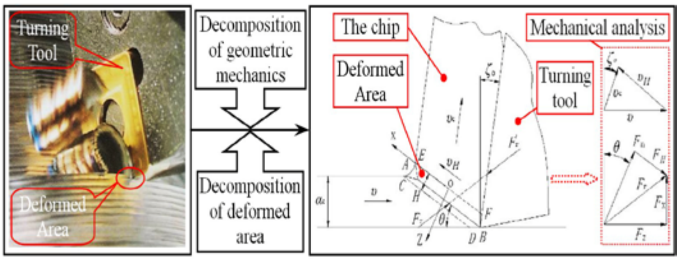


Fig. 1 Schematic diagram of deformation of the cutting area in super-heavy powerful turning process

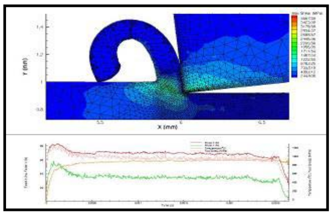
Since the cutting scraps contiguously pass through the deformation zone at a higher speed, the shear zone will produce a lot of heat. Therefore, when analysing the shear stress, we must consider the impacts of temperature [5], and that the deformation temperature of the shear zone *AB* can be calculated by Eq. 2 [6]:

$$T_{AB} = T_Y + \frac{\tau}{\rho c \upsilon \sin\theta}\int_{\frac{H}{2}}^{H} R(z)\delta(z)dz \tag{2}$$

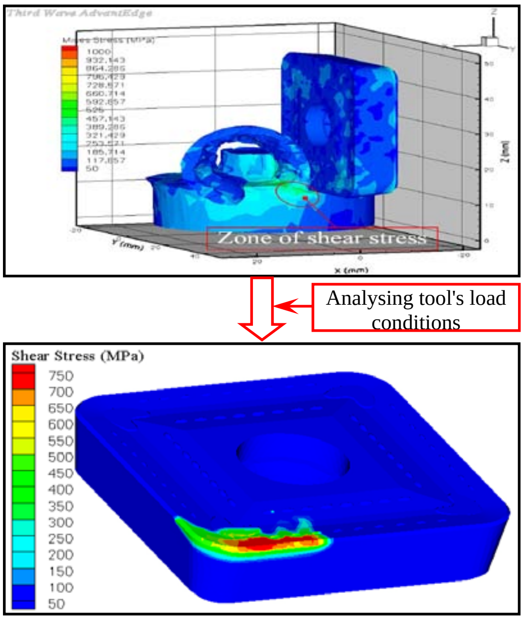
According to the relationship of shear flow stress τ_{AB}, shear strain rate δ_{AB}, shear strain γ_{AB} and temperature models, finite element simulation analyses of cylindrical shell section material can be undertaken through the Third Wave in the laboratory (as shown in Fig. 2).

From Fig. 2-a, it can be seen that the shear flow stress of the cylindrical shell section material 2.25Cr-1Mo-0.25V steel shows a trend of decrease with the increase of cutting

temperature, and the force of the tool in cutting zone remains stable if the temperature is constant. Therefore, the influence of temperature on the shear flow stress is relatively large.



a) Simulation analysis of the cutting



b) Shear stress distribution of the zone of cutting deformation

Fig. 2 Finite element analysis of the super-heavy powerful turning process

Since the stress distribution of the shear zone in Fig. 2-b is basically in line with that of the first deformation zone, the shear stress of the cutting zone mainly passes from the tool nose to the flank surface of cutting tool. From Fig. 2, it can also be seen that the main factor that affects the state of the tool is dynamic shear stress. In order to verify the results from the computer simulation, dynamic cutting experiments are undertaken. The experimental materials and the selection of parameters are listed in Table Ⅰ and Table Ⅱ respectively. And the type of tested tool is XF8 which is the cemented carbide heavy-duty turning cutter of composite coatings shown in Fig. 3. Then the experimental results are shown in Fig. 4 and Fig. 5, respectively.

TABLE I MECHANICAL PROPERTIES OF THE EXPERIMENT MATERIAL

Materials	**Heat-treated condition**	**Hardness [HB]**	σ_s **[MPa]**	σ_b **[MPa]**	δ **%**
2.25Cr-1Mo-0.25V steel	Quenching and tempering	235	809.7	760	18
45 steel	Normalization	163~218	285.4	568.9	15

TABLE II SELECTION OF PARAMETERS AND CUTTING TOOL

<table>
<tr><th>Tool Model</th><th>γ_0</th><th colspan="2">α_0</th><th colspan="2">λ_s</th><th colspan="2">γ_ε</th><th colspan="2">Coating type</th></tr>
<tr><td>XF8</td><td>13°</td><td colspan="2">0°</td><td colspan="2">0°</td><td colspan="2">0.8</td><td colspan="2">4225</td></tr>
<tr><td rowspan="2">Cutting parameters</td><td>Cutting speed v [m/min]</td><td colspan="4">Feed rate f [mm/r]</td><td colspan="4">Cutting depth a_p [mm]</td></tr>
<tr><td>60</td><td>0.1</td><td>0.2</td><td>0.3</td><td>0.4</td><td>0.3</td><td>0.5</td><td>0.8</td><td>1.0</td></tr>
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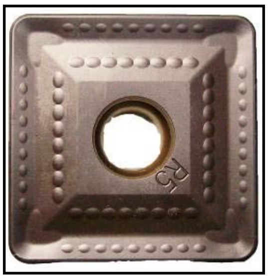
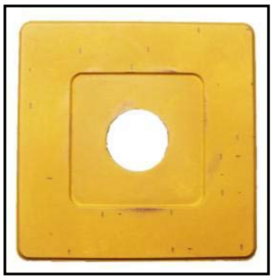


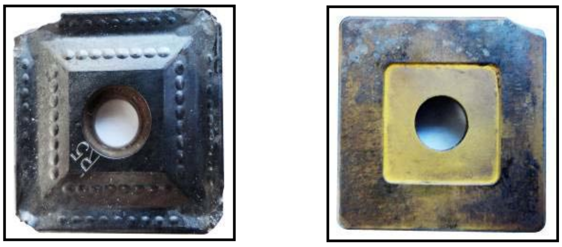
a) Rake face of XF8 tool



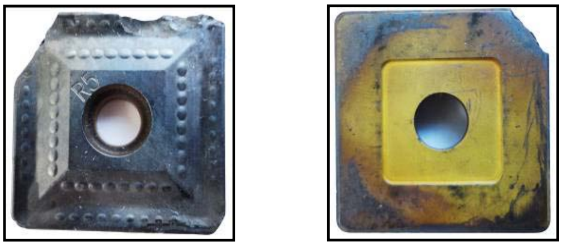
b) The bottom of XF8 tool

Fig. 3 The super-heavy powerful turning cutter of composite coating

a) Broken cutter in the condition of low speed



b) Broken cutter in the condition of moderate speed



c) Broken cutter in the condition of moderate-high speed

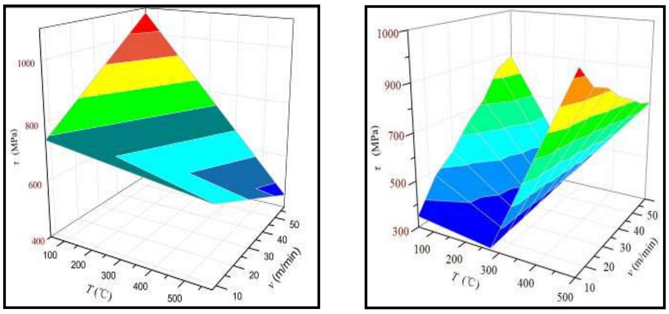
d) Broken cutter in the condition of super high speed

Fig. 4 Broken cutters in the process of super-heavy powerful turning test

As there are lots of forging defects on the surface of hydrogenated cylindrical shell, and when the cutting depth applied is constant, the actual cutting depth changes greatly. Whereas the particularity of cutting process, the stable cutting depth is adopt in this test. Yet, the damaged form of the super-heavy powerful turning cutter under the condition of low speed is shown in Fig. 4-a. It shows that the dynamic load impact the cutter withstand is relatively small in this condition, and there are slight cracks being generated in cutting edge. The Fig. 4-b and Fig. 4-c separately show that the damaged form of the super-heavy powerful turning cutter in condition of moderate and moderate-high speed. Seen from these two pictures, the mainly damaged forms of the cutters are the

cutter-point's being broken and cutting edge's crush. Further analysis shows that the dynamic-variable load energy is more scattered in this case. However, the most serious result is referred in Fig. 4-d, this explains that higher cutting speed makes dynamic-variable energy release in a moment and act on cutting area intensively. Therefore, the damaged form of the super-heavy powerful turning cutter appears the phenomenon that the failure entrains as an umbrella-type from the geometric centre of the cutter to cutting edge.

In Fig. 5, γ、δ and T are the shear strain; shear strain rate and deformation temperature of the materials, respectively. From Fig. 5, we can see the shear flow stress of 2.25Cr-1Mo-0.25V steel decreases with the increase of temperature, but that of the 45 steel increases with the increase of temperature. So, 2.25Cr-1Mo-0.25V steel has thermo-softening effects, which is consistent with its thermal toughness property. This is unfavourable for tool cooling and more likely to cause tool fatigue failure.



γ =1.10, δ =35948s^{-1}
a) 2.25Cr-1Mo-0.25V steel

γ =1.38, δ =21655s^{-1}
b) 45 steel

Fig. 5 Effect of cutting temperature on shear flow stress

III. THE FAILURE CONDITIONS OF TOOL UNDER THE CONDITIONS OF DYNAMIC CHARACTERISTICS

In the process of super-heavy powerful turning, fracture is the main failure form of super-heavy powerful turning cutters, that is, it will induce damage failure. According to analyses, the impact damage of turning cutter is mainly caused by the changes of shear stress caused by dynamic variable load, so it mainly shows as shear fractures along the direction of the flank surface. The damage of the shear stress is a relative sliding process of the material under the effect of a shear stress, so we can use elasticity theory to analyse the plane shear stress of the cutting zone for turning cutters (as shown in Fig. 6).

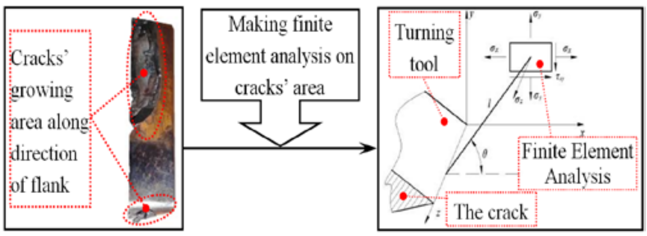


Fig. 6 Analysis of shear stress of crack tip on machining region of the cutter

According to the geometric relationship in Fig. 6, the Eq. 3 can be introduced to calculate the dynamic shear stress under the conditions of the super-heavy powerful turning [7, 8]:

$$\tau = \frac{\sqrt{2}}{3}\Big[\sigma_x^2+\sigma_y^2+\sigma_z^2-\sigma_x\sigma_y-\sigma_x\sigma_z -\sigma_y\sigma_z+3\left(\tau_{xy}^2+\tau_{xz}^2+\tau_{yz}^2\right)\Big] \quad (3)$$

With the effect of flow shear stress, the dynamic stress components near the tip of fatigue crack on the blade are as follows:

$$\sigma_x = \frac{\xi_i}{\sqrt{2l}}\cos\frac{\theta}{2}\left(1-\sin\frac{\theta}{2}\cos\frac{3\theta}{2}\right) - \frac{\xi_j}{\sqrt{2l}}\sin\frac{\theta}{2}\left(2+\cos\frac{\theta}{2}\cos\frac{3\theta}{2}\right) \quad (4)$$

$$\sigma_y = \frac{\xi_i}{\sqrt{2l}}\cos\frac{\theta}{2}\left(1+\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right) + \frac{\xi_j}{\sqrt{2l}}\sin\frac{\theta}{2}\cos\frac{\theta}{2}\cos\frac{3\theta}{2} \quad (5)$$

$$\tau_{xy} = \frac{\xi_i}{\sqrt{2l}}\cos\frac{\theta}{2}\sin\frac{\theta}{2}\cos\frac{3\theta}{2} + \frac{\xi_j}{\sqrt{2l}}\cos\frac{\theta}{2}\left(1-\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right) \quad (6)$$

$$\tau_{yz} = \frac{\xi_k}{\sqrt{2l}}\cos\frac{\theta}{2} \quad (7)$$

$$\tau_{xz} = -\frac{\xi_k}{\sqrt{2l}}\sin\frac{\theta}{2} \quad (8)$$

When the Eq. 4, Eq. 5, Eq. 6 and Eq. 7, Eq. 8 are input into the Eq. 3, the Eq. 9 will be obtained:

$$\tau = \frac{1}{\sqrt{l}}\left(\lambda_{ii}\xi_i^2+\lambda_{ij}\xi_i\xi_j+\lambda_{jj}\xi_j^2+\lambda_{kk}\xi_k^2\right)^{\frac{1}{2}} \quad (9)$$

Here, factors in the equation 9 can be expressed as follows (referred with: Eq. 10):

$$\begin{cases}\lambda_{ii}=0.14+0.06\cos\theta-0.08\cos^2\theta\\ \lambda_{ij}=0.33\cos\theta\sin\theta-0.11\sin\theta\\ \lambda_{jj}=0.14-0.06\cos\theta+0.25\cos^2\theta\\ \lambda_{kk}=0.33\end{cases} \quad (10)$$

Suppose $\eta=\lambda_{ii}\xi_i^2+\lambda_{ij}\xi_i\xi_j+\lambda_{jj}\xi_j^2+\lambda_{kk}\xi_k^2$. According to the critical condition of plastic deformation of metal materials, we can obtain the distance from the tip of fatigue crack to the edge of the plastic zone:

$$l = \frac{9}{2\sigma_s^2}\eta \quad (11)$$

Because the growth direction of the blade crack is the shortest parallel line between the tip of blade crack and the edge of the plastic zone, the condition of having crack extension can be got as follows:

$$\begin{cases}\dfrac{dl}{d\theta}=0\\[2mm] \dfrac{d^2l}{d\theta^2}>0\end{cases} \quad (12)$$

According to the analyses, the fracture failure of super-heavy powerful turning cutter occurs because of the fatigue cracks caused by dynamic shear stress and eventually leads to the tear of the material in cutting zone. So, the fracture of super-heavy powerful turning cutter is a process of crack generation-crack growth-material tear. Based on the fracture criterion of plane shear stress intensity factor in elastic mechanics, suppose ξ_j=0 in Eq. 9 and get this formula:

$$\eta = \left(0.14 + 0.06\cos\theta - 0.08\cos^2\theta\right)\xi_i^2 + 0.33\xi_k^2 \quad (13)$$

Combining Eq. 11 with Eq. 12, when θ = 0, the ultimate shear stress intensity factor of super-heavy powerful turning cutter can be obtained as follows:

$$\eta_{\lim} = 0.11\xi_i^2 + 0.33\xi_k^2 \quad (14)$$

Therefore, under the conditions of dynamic characteristics, the critical condition of fracture failure for super-heavy powerful turning cutter is as follows:

$$\frac{\xi_i^2}{\xi_{i\lim}^2} + \frac{3\xi_k^2}{\xi_{i\lim}^2} = 1 \quad (15)$$

Where, $\xi_{i\lim}^2 = \sigma_s^2\lambda$ and $\xi_k^2 = \tau^2\lambda$.

During super-heavy powerful turning process, dynamic cutting force works on turning cutters. The shear flow stress of the dynamic variable load in the cutting zone can easily lead to the fatigue of the turning tool, and cause cracks. When working load reaches the critical condition of fracture, the turning cutter will produce fractures (as shown in Fig. 7).

a) Fracture of side-cutting edge is very serious

b) The fracture extending from the tip to both sides of the cutter evenly

Fig. 7 State of fracture failure of the super-heavy powerful turning cutter

From Fig. 7, it can be seen that the fracture of super-heavy powerful turning cutter is along the direction from the cutter nose to the flank surface of turning cutter, which is also in line with the previous analysis that shear stress passes from the cutter nose to the flank surface of cutting cutter. And the material on the flank surface drops off more seriously, which is caused by the crack extension from the cutter nose to the flank surface of the turning cutter. In general, the blade fracture usually appear with a well-distributed torn from cutter nose to the main and side cutting edge, but occasionally there will be more serious fractures on the side cutting edge (as shown in Fig. 7-a). This is mainly because the rugged forging defects on the surface of the cylindrical shell section continuously impact the side cutting edge.

IV. CONCLUSIONS

The dynamic cutting force of efficient machining under the super-heavy powerful turning condition is the main factor that causes cutter fracture. Through the cutting experiments of 2.25Cr-1Mo-0.25V steel as well as the study of cutter failure form, we can see:

The cutting temperature of cutting 2.25Cr-1Mo-0.25V steel is relatively high, and the high temperature can easily lead to the softening of the material, thus affecting the shear flow stress in the cutting zone. Under the condition of dynamic characteristics, when both the shear strain and shear strain rate of the cutter reach to the strength limits of the cutter, fatigue fractures will appear. Therefore, the main failure form of the cutter is shear fractures.

Proposing the intensity factor of plane shear stress for super-heavy powerful turning based on elasticity theory and calculating the critical condition of fatigue fracture for super-heavy powerful turning cutter provides a basis for the judgment of the fracture failure of turning tools.

ACKNOWLEDGMENT

This research is supported by the National Natural Science Foundation of China (Project approval number: 51175131) and National High Technology Research and Development Program ("863"Program: 2009AA044302).

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- Won the first prize in the competition of research papers which was held by college.
- Obtained the "Outstanding Graduates" honor of university in April 2011.
- Obtained the "Provincial Outstanding Graduates" honor in May 2011.
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